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Willy Bertiger, Sien Wu, Tom Yunck, Ron Muellerschoen, Pascal Willis*, Yoaz Bar-Sever, A. Davis, Bruce Haines, Tim Munson, Steve Lichten, and Rick Sunseri

Jet Propulsion Laboratory
Pasadena, CA

*Institut Geographique National (France)

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EARLY RESULTS FROM THE TOPEX/POSEIDON GPS PRECISE ORBIT DETERMINATION DEMONSTRATION

Willy Bertiger*, Sien Wu‡, Tom Yunck§, Ron Muellerschoen*, Pascal Willis††, Yoaz Bar-Sever*, Ab Davis†, Bruce Haines*, Tim Munson*, Steve Lichten**, and Rick Sunseri*

TOPEX/POSEIDON, a US/French oceanographic mission launched in August 1992, is the first earth satellite to carry a multi-channel, dual frequency GPS receiver capable of making high precision P-code pseudorange and carrier phase measurements. The receiver was placed on TOPEX/POSEIDON as an experiment to demonstrate the potential of differential GPS tracking for subdecimeter orbit determination. In addition to the receiver, TOPEX/POSEIDON carries two flight-proven tracking systems to provide the operational precise orbit determination needed to meet the mission scientific requirements. These include a French-built one-way Doppler system known as DORIS and a circular ring of laser retroreflectors. Here we evaluate the quality of the GPS-determined orbits by examining post-fit residuals, orbit comparisons with DORIS, and orbit repeatability on overlapping data arcs. Overlapping data arcs with 6 hrs of common data out of a 30 hr arc have an average RMS altitude difference of 3.0 cm for 9 arcs. The average RMS altitude difference about the mean with a DORIS orbit was 5.7 cm.

INTRODUCTION

TOPEX/POSEIDON, a US/French oceanographic mission, was launched on August 10, 1992. A principal objective is to measure ocean surface height with a radar altimeter, which is precise to about 2.5 cm. To exploit this altimeter precision the radial position of TOPEX/POSEIDON is required to be better than 15 cm RMS[1]. Tracking at this level of accuracy requires precise models of satellite dynamics if the traditional solution methods for satellite laser ranging (SLR) or Doppler data are used. Much work has gone into improvement of dynamical models for TOPEX/POSEIDON, including the new gravity field

* Member of the Technical Staff, Jet Propulsion Laboratory
‡ Technical Group Leader, Jet Propulsion Laboratory
§ Deputy Section manager, Jet Propulsion Laboratory
†† Head Geodetic Research Laboratory, Institut Geographique National (France)
† Topex-GPS Experiment manager, Jet Propulsion Laboratory
** Group Supervisor, Jet Propulsion Laboratory

JGM-1[2] and a dedicated model of the radiation forces acting on the spacecraft[3,4]. The continuous 3-dimensional coverage offered by the Global Positioning System (GPS) permits a reduced dependence on dynamic models. The techniques for tracking a low earth orbiter with GPS have been refined over the years[5-7]. TOPEX/POSEIDON is the first opportunity to demonstrate these techniques with a high quality flight receiver[8].

Instead of relying solely on the physical models describing the forces acting on the spacecraft, the optimal GPS technique uses 3-D geometric information to correct for force model errors[5-7]. This technique, known as *reduced dynamic tracking*, is carried out by solving for an ad hoc 3-D acceleration on TOPEX/POSEIDON at each measurement epoch. These accelerations are modeled in the filter as a random process in which the correlation time and the apriori uncertainty of the accelerations may be adjusted to optimize the solution. The better the deterministic force model, the tighter the constraints may be on the stochastic accelerations.

We have now processed 12 days of TOPEX/POSEIDON GPS data with this technique, achieving an RMS agreement of 3.0 cm, 3.4 cm, and 6.5 cm in altitude, cross track and along track components on 6-hr overlapping segments of 30 hr solution arcs. The postfit RMS residuals for the GPS carrier phase measurement between the flight receiver and the transmitting GPS satellites are consistently between 4 and 5 mm.

MEASUREMENT SYSTEM

Figure 1 depicts the major components of the differential GPS tracking system. There are currently 22 GPS satellites transmitting radio signals at two frequencies, L1 (1575.42 MHz) and L2 (1227.6 MHz). These signals are modulated by pseudorandom ranging codes (the P-codes), which permit one-way range (also known as pseudorange) measurements to be made. For additional details on the signal characteristics see Ref. 9. Precise orbit determination at the decimeter level with GPS requires use of a ground reference network of receivers which continuously track GPS. Data from the ground and flight receivers are then brought together and processed simultaneously. For the results discussed in this paper, we used a ground reference network consisting of the 14 sites shown in Fig. 2, equipped with Rogue and TurboRogue dual-frequency P-code receivers[10,11]. Harvest and Quincy were included to help in the effort to calibrate the Topex altimmeter. Harvest is an offshore oil platform that contains instrumentation used in calibration. Quincy is a site in California used to tie Harvest to a global reference frame.

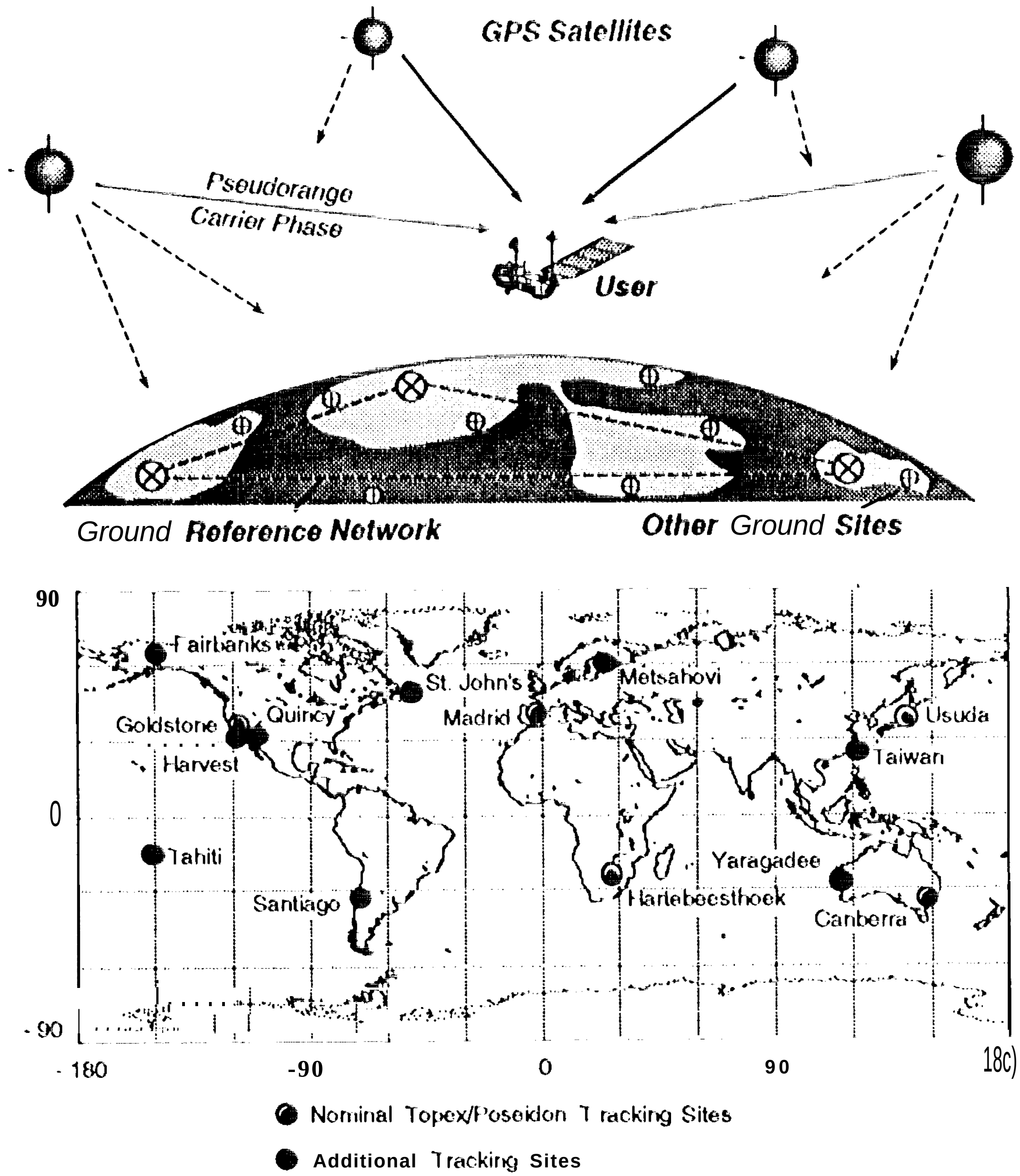

Fig. 2 GPS Ground Network for TOPEX/POSEIDON Tracking

Using data from both frequencies to calibrate the ionospheric delay, the flight receiver measures the range between the phase center of its antenna and the GPS satellite ante.nna, plus the offset between the transmitter and receiver clocks (pseudorange). The ground receivers see an additional delay caused by the earth's troposphere. In addition to the pseudorange, the receivers continuously measure the phase of the L-band carriers. Ibis carrier phase measurement is identical to the pseudorange measurement except that it is about one hundred time.s more precise and has an arbitrary bias resulting from the unknown number of whole cycles between the transmitter and receiver, the initial phase bias, and various instrumental delays. The observable are therefore

$$pseudorange = range + clock\_offset + troposphere + noise \qquad [1]$$

$$carrier\_phase = range + clock\_offset + troposphere + bias + small\_noise \qquad [2]$$

These two equations are. simplified versions of the actual model for the measurements. A complete description is given in Ref. 12.

Signals from up to six GPS satellites are received simultaneously by the GPS Demonstration Receiver (GPSDR)[8] on TOPEX/POSEIDON. At least 5 GPS satellites are observed 80% of the time and at least 4 are observed 96% of the time. Note that with 4 GPS being observed, if we were not adjusting any other parameters we could determine the satellite position and clock at each measurement time. Of course this is not the optimal strategy, but it gives an idea of the basic power of GPS compared to both S1 .R and DORIS which do not have continuous coverage or observations in many directions at one time. Each Rogue or TurboRogue receiver on the ground can observe up to 8 GPS satellites simultaneously. Typically a ground receiver is observing 5 or more GPS satellites 90% of the time and 6 or more 72% of the time. Carrier phase. measurements on TOPEX/POSEIDON are recorded every second, while pseudorange measurements are. smoothed and recorded every 10 seconds.

The ground receivers record both data types every 30 seconds, again smoothing pseudorange measurements against the carrier over the full interval. The GPSDR data are taken at the higher data rate in order to interpolate measurements accurately to a common time with the ground network while frequency dithering under selective availability (SA) is active. This is necessary because the clock onboard TOPEX/POSEIDON is not regularly reset, and may drift by large amounts (seconds) with respect to time kept on the. ground, leading to asynchronous sampling between the flight and ground receivers. With accurate interpolation to common times the effects of SA are effectively removed [13] in the subsequent differential processing. SA introduces a frequency variation in the GPS satellite clock, which we can observe and removed with simultaneous ground data.

Data from both the ground network and GPSDR are compressed in a preprocessing step to a 5 minute interval. In this step, the pseudorange data are again smoothed against the carrier to improve precision, which typically reaches 20 cm for the dual frequency ground pseudorange and 70 cm for the flight data, after S-rein compression. Because of the inherently high precision of the phase. data, no smoothing of phase is attempted. Phase point.. are simply selected at five minute intervals, giving typical system noise of 0.2 mm for the dual-frequency ground data and 2 mm for the flight data.

DATA PROCESSING SOFTWARE AND MODELS

Data processing was performed with the GIPSY-OASIS II analysis software[12,16] and an orbit integrator written by Sunseri[19]. The main components of the analysis software are a GPS data editor, orbit integrator, measurement model generator, and filter/smoother. Tie. data editor operates on a combined set of dual frequency GPS phase and pseudorange measurements and detects outliers and carrier phase discontinuities[16].

The orbit integrator performs a numerical integration of the satellite mbit using a nominal initial state and a set of high accuacy models of the forces acting on the satellite, It also computes partial derivatives of the current state of the spacecraft with respect to the dynamical and epoch state parameters. This initial trajectory and the partial derivatives are written to a file to be read by the measurement model program,

The force models for TOPEX/POSEIDON include the JGM-1 gravity model developed at the Goddard Space Flight Center and the. University of Texas at Austin specifically for TOPEX/POSEIDON[2], atmospheric drag, Earth albedo, solar radiation pressure, and thermal radiation emitted by the satellite[4,5]. In addition to these forces, there is an empirical acceleration parameter, $\vec{a}$, of the form

$$\vec{a} = \vec{C} + \sum_{i=1}^{2} \vec{A}_i \cos \omega_i t + \vec{B}_i \sin \omega_i t \qquad [3]$$

where $\vec{C}$, $\vec{A}_i$, and $\vec{B}_i$ are constant vectors in the coordinate system oriented in the nominal spacecraft along track, radial, and cross track directions. The frequencies ω_i are once and twice per revolution of TOPEX/POSEIDON and t is time past an-epoch. Partial derivatives of the current state with respect to the coefficients $\vec{C}$, $\vec{A}_i$, and $\vec{B}_i$ are computed. In addition, partial derivatives of the GPS satellite current states with respect to their epoch states and the Rock IV solar pressure model[14,15] are computed.

After editing, the data are compressed to a 5 minute rate and the dual frequency ionosphere free combinations of phase and pseudorange are formed. In the compression step the pseudorange data are smoothed against the carrier over the entire S-rein interval, while the phase is simply sampled at the appropriate times. The nominal trajectory is then used to compute model GPS observable and partial derivatives of those observable with respect to the adjusted parameters. The observable model program reads spacecraft postions and partials with respect to dynamical and epoch state parameters from the file written by the integrator, In addition to partials of the observable with respect to dynamical parameters, partial derivatives of the observable are computed with respect to ground station position, zenith troposphere delay, earth orientation, the geocenter, GPS clocks, and receiver clocks. The model includes relativistic effects, solid-earth tides, pole tides, phase. windup due to antenna rotation, and antenna phase-center variation as a function of azimuth and elevation,

Following the modeling step, the filter/smoother is executed to estimate a large set of parameters (specified by the user), adjusting them to minimize the mean squared difference between the GPS observations and the computed model. In its simplest form the filter/smoother would produce a conventional least squares solution; but to obtain a more accurate orbit some parameters are treated as stochastic processes using a Square Root Information Filter (SRIF) formulation.[24] The parameters adjusted in our standard solution strategy are summarized in Table 1.

In these solutions, all clock.. in the system are modeled as white noise processes with no apriori constraint, except for one which is held fixed as a reference clock (hydrogen maser at Fairbanks), The zenith troposphere delay at each ground station is modeled as a random walk which allows 1 cm/hour change in the zenith delay. For the 30-hour data arcs, the parameters of the Rock IV solar pressure model are treated as colored process noise with a 4 hour correlation time and sigma of 10% at each batch time. For data arcs shorter than 30 hours these parameters are treated as constants

In the reduced dynamic solution, the TOPEX/POSEIDON state and the empirical constant and once- and twice-per-revolution accelerations (Eq. 3) are first adjusted to convergence, which generally takes two or three iterations through the filter producing a dynamic solution. This iteration of the dynamic solution is performed so that the final adjustment of stochastic accelerations will be in (or very close to) the linear regime. In the last (reduced dynamic) step, a final adjustment is made of the TOPEX/POSEIDON state and all other previously adjusted parameters, *except for the empirical once- and twice-per-rev parameters,* which are now held_ fixed. Instead, a stochastic adjustment of the constant accelerations is performed (C, Eq. 3). These accelerations are given a correlation time of 15 min with batch-to-batch sigmas of 10 nanometers/sec^2 in the radially and 20 nm/s^2 in the. cross and along track directions for the 30 hour arcs. In earlier results with 24 hour arcs, sigmas of 25, SO, and 50 nm/s^2 were used. It is the geometric strength of the GPS observations that allows these arbitrary final adjustments.

T BLE 1. SUMMARY OF ADJUSTED PARAMET RS

Topex/Poseidon	GPS	Ground Station	Earth
state	state	Location	Polar Motion
Clock	Clock	Clock	UT1-UTC rate
empirical acceleration	Rock IV solar press.	Troposphere	Polar Motion rate
stochastic acceleration			

TESTS

Residuals

Figures 3 and 4 show the GPSDR residuals for a typical 30 hour arc to each GPS satellite in view. Fig, 3 gives the phase residuals for the converged dynamic solution, Note that there is some information left in the residuals when compared the the receiver system noise of 2 mm. After the final reduced dynamic adjustment we see an RMS phase residual of 4.3 mm.

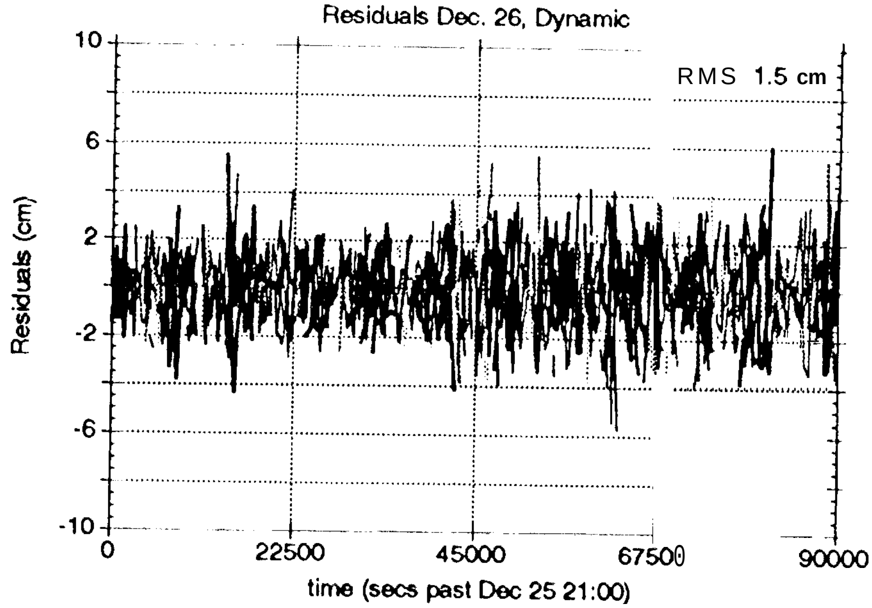

Fig. 3 GPSDR Dynamic Ionosphere Free Phase Residuals

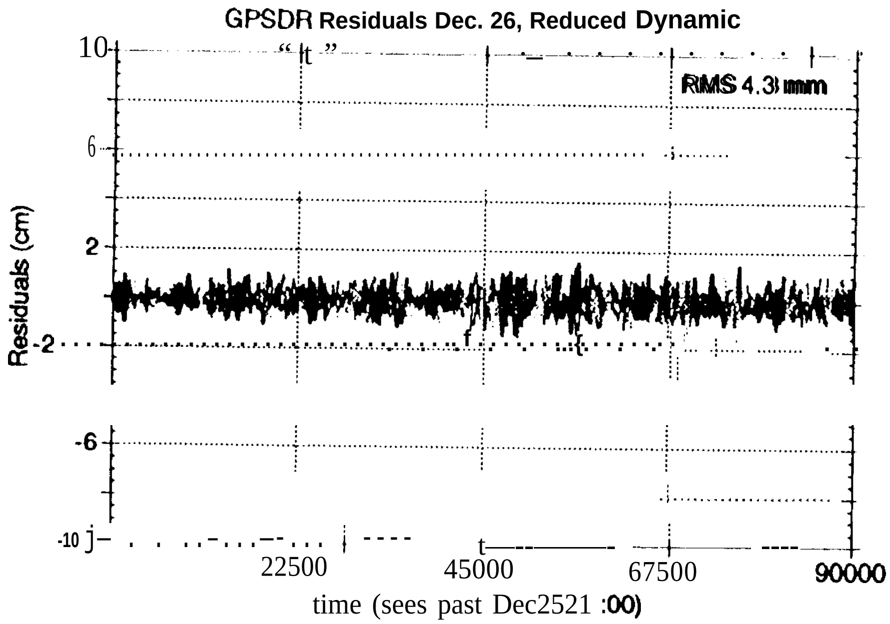

Fig. 4 GPSDR Reduced Dynamic Ionosphere Free Phase Residuals

comparisons with DORIS

DORIS is a precise one-way Doppler tracking system onboard TOPEX/POSEIDON. This system was first tested 1990 on the French remote sensing satellite SPOT2, and has proven very accurate for orbit determination[20] and for precise point positioning[21,23]. It is the operational French precise tracking system for **TOPEX/POSEIDON.**

Two important differences between DORIS and GPS are: DORIS is an up-link system (the signal is transmitted from the ground to the satellite, in order to avoid costly ground telecommunications) and DORIS provides Doppler (range rate) data only[22]. Presently the DORIS tracking network consists of 42 permanent sites, providing nearly continuous 1-dimensional tracking of **TOPEX/POSEIDON.**

In order to evaluate the GPS reduced dynamic orbit, a DORIS orbit was generated for 3 test days with the GIPSY-OASIS II software. Estimated parameters included the epoch state vector (position and velocity of the satellite), a constant empirical along track acceleration, once-per-rev empirical accelerations in the along track and cross track directions, and zenith tropospheric delay and clock rate parameters for each station for each pass. Earth rotation parameters were held fixed to the IERS Bulletin B final values. The typical RMS for the DORIS postfit residuals was 0.5 mm/s (a bit bigger than the thermal noise level of 0.3 mm/s).

The DORIS dynamic and the GPS reduced dynamic solutions were computed in an inertial coordinate frame and difference. The result showed a 2.3 cm bias and a S.5 cm standard deviation, In this comparison, it should be noted, many factors are different: data type, tracking network, and data analysis strategies. Table 2 summarizes the comparison.

TABLE 2. RADIAL ORBIT DIFFERENCE DORIS - GPS REDUCED DYNAMIC, 24 HOUR ARC

Day of Year (1992)	Mean Difference(cm)	Std. Deviation(cm)
280	-2.6	4.9
288	-2.0	5.4
290	-2.4	6.7

For oceanographic purposes, only the radial component of the orbit is important. For orbit comparisons, however, it is also important to examine the cross-track and along track components (to look for terrestrial reference frame differences, for example). Fig. 5 shows the difference over time of the DORIS dynamic and GPS reduced dynamic orbits. A once-per-revolution signature appears prominently in the cross track difference but is more subdued in the altitude and along track components.

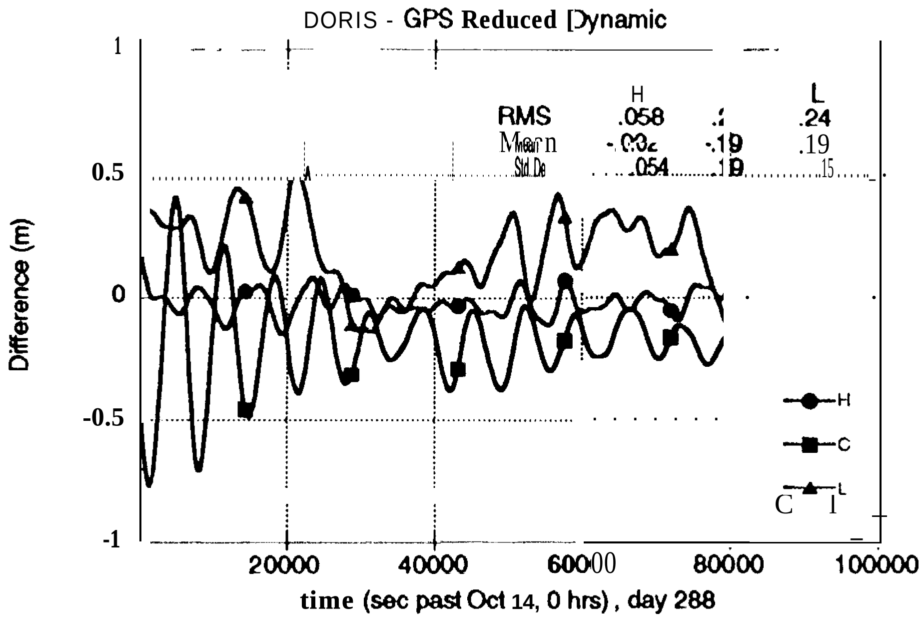

Fig. 5 DORIS - **GPS Reduced Dynamic, Oct. 14**

H - Altitude, C - Cross Track, L - Along Track

<u>Overlapping Arcs</u>

Since the dominant error source in DORIS tracking is expected to be mismodeled dynamics, other tests to are needed asses the accuracy and precision of the GPS reduced dynamic solutions. One such test is overlapping data arcs. For the period of Dec. 21 to Dec. 29, 1992, we have processed nine 30-hr GPS data arcs with 6 hrs of overlap between arcs, as indicated in Fig. 5. The RMS differences over the 6-hr overlaps for all three components are shown in Fig. 6. The average for the eight overlaps is 3.0 cm in altitude,

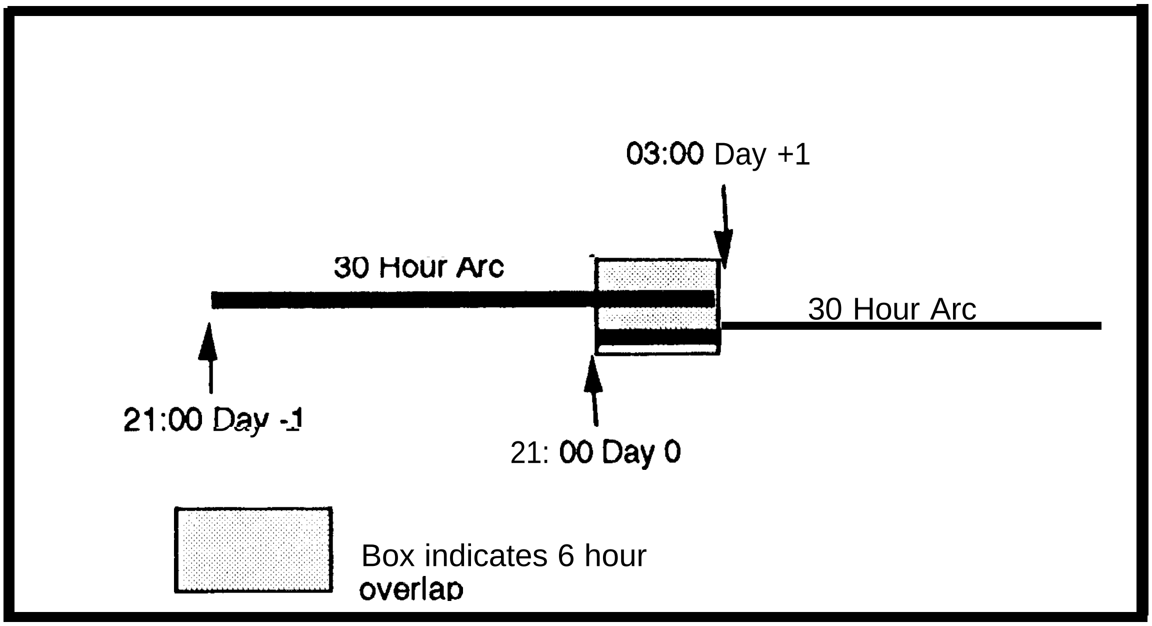

Fig. 5 Overlapping Data Area

3.4 cm in cross track, and 6.5 cm in along track. The postfit residuals for the GPSDR phase measurements are typically 4-5 mm. From that value alone on might expect smaller RMS orbit discrepancies on the overlaps, but that does not take into account the errors in GPS orbits. Figure 7 shows the average for all GPS satellites of the 3-D RMS overlap difference for the same 6-hr overlap periods. Errors in GPS orbits do not translate directly into errors in the TOPEX/POSEIDON orbit but are reduced by roughly a factor of ten.

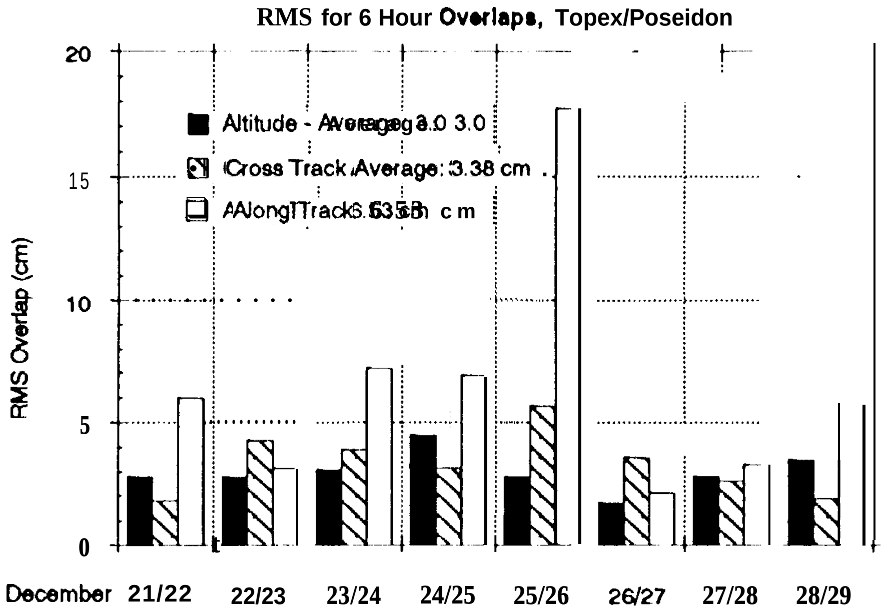

Fig. 6 RMS Difference Over 6 Hours for Overlapping 30 Hour Arcs

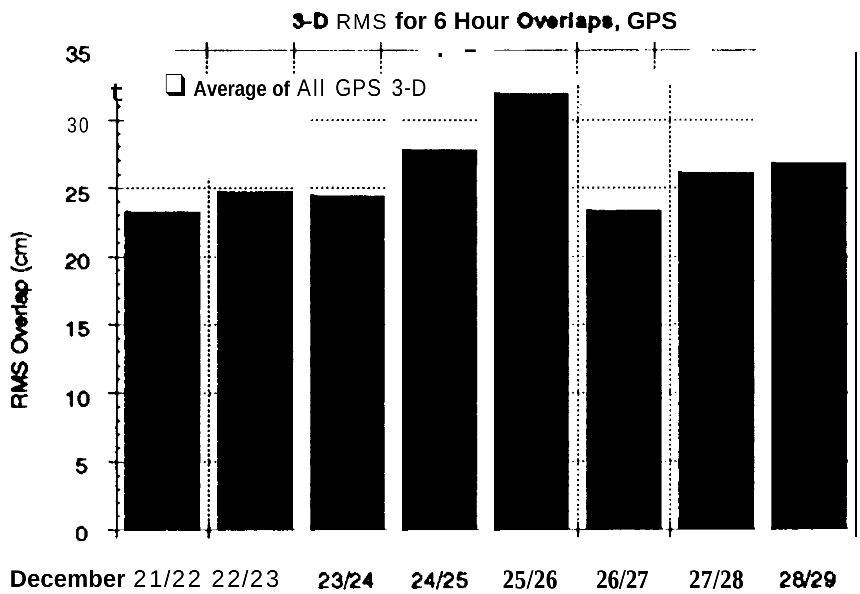

Fig. 7 3-D GPS RMS DifferenceOver 6 Hours for Overlapping 30 Hour Arcs

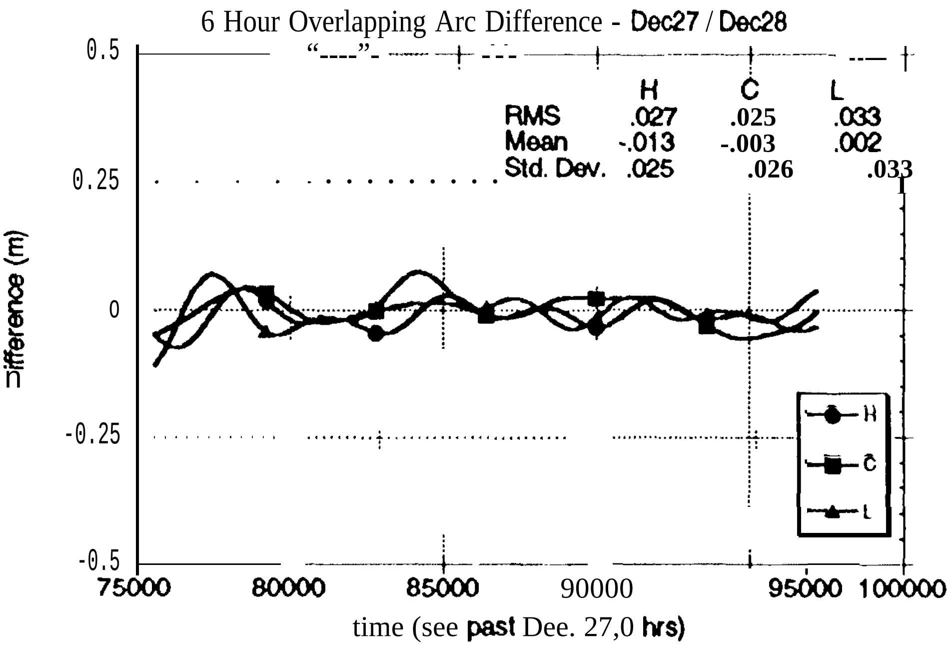

Fig. 8 Difference of Two 30 hour arcs with 6 hours of common data

H - **Altitude,** C - Cross **Track, 1.. Along Track**

Figure 8 shows the difference of a 30 hour arc centered on Dec. 27 and the one centered on Dec. 28. We will investigate the systematic nature of the difference in the orbits in future work,

CONCLUSIONS

The results in this paper are preliminary. Much more data must be analyzed and many more comparisons made both with DORIS and with SLR orbits before we can draw any firm conclusions. Based on the analyses to date, we estimate the typical GPS reduced dynamic orbit precison precision to be 3-4 cm in altitude, 4-6 cm in cross track, and 6-8 cm in along track. Comparisons with the DORIS tracking system indicate an accuracy S-7 cm in altitude.

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